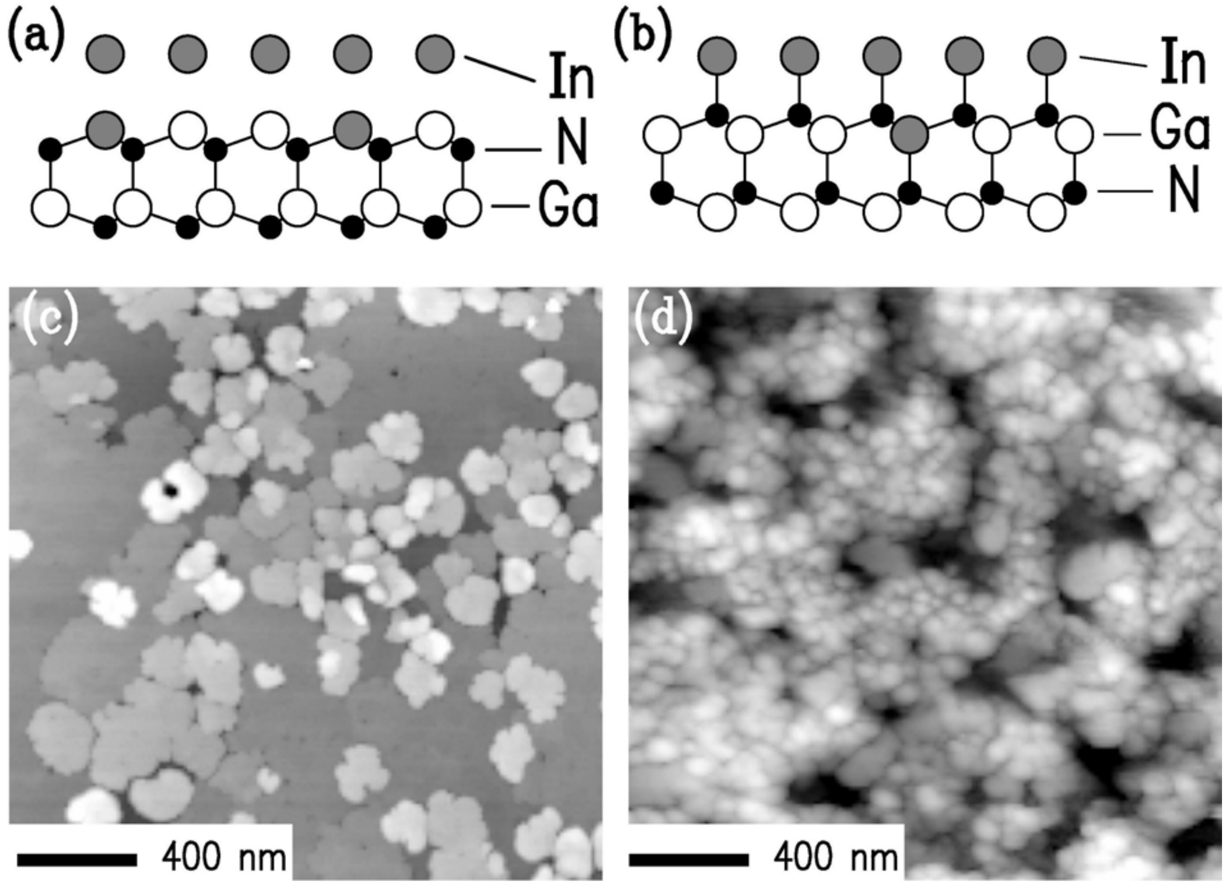
Enhanced Lateral Diffusion of Indium on GaN

(0001) surface

smooth growth



($000\bar{1}$) surface

rough growth

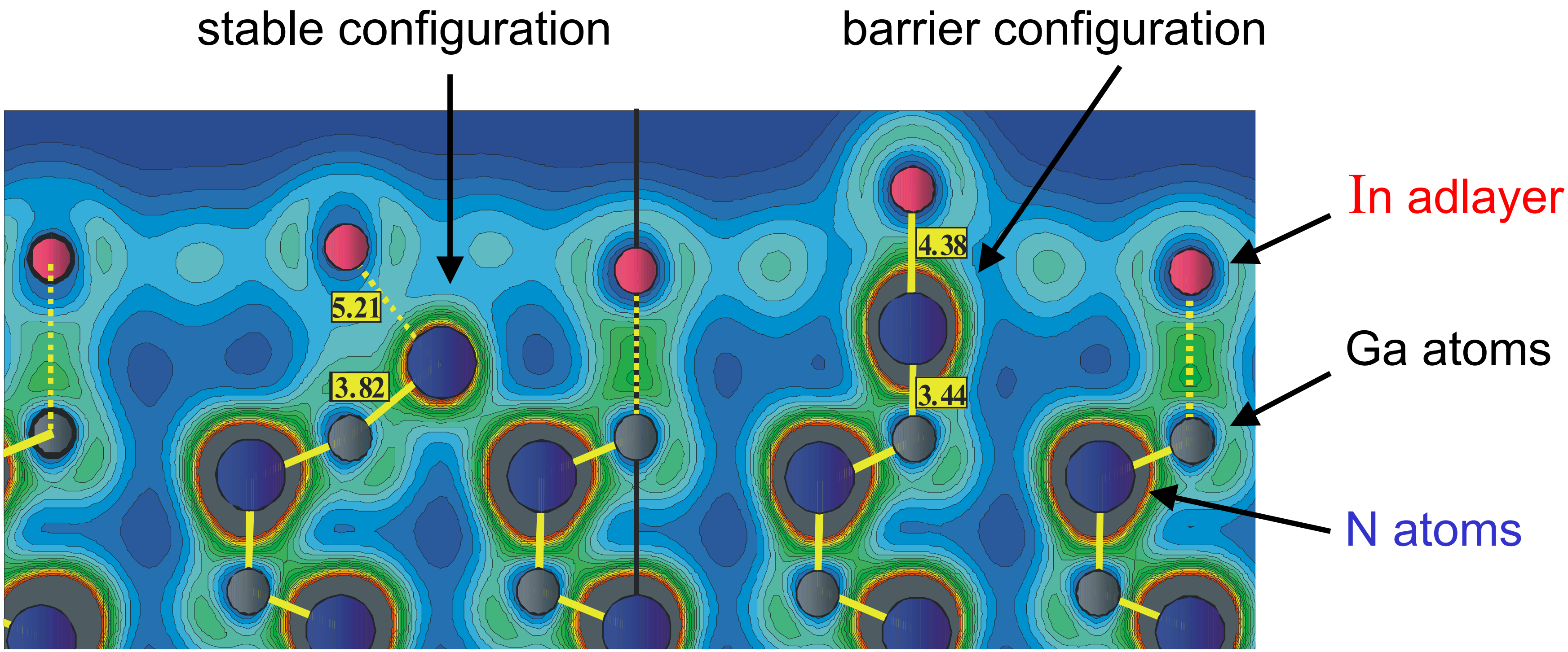
- structure of (0001) and ($000\bar{1}$) surfaces known from STM studies
- theory indicates N diffuses *between* metal layers for GaN(0001)

We have discovered a new diffusion mechanism which occurs during epitaxial growth, and for the case of InGaN(0001) it leads to a smooth morphology during growth. This new mechanism involves the diffusion of adatoms *within* a liquid-like metallic layer which exists on the (0001) surface of GaN but does not exist (0 0 0 -1) surface of GaN. The structure of both of these surfaces in the presence of indium is shown in panels (a) and (b), as known from our previous works (H. Chen, et al. MRS Internet J. Nitride Semicond. Res. 4S1, G9.5 (1999) and J. Vac. Sci. Technol. B 18, 2284 (2000)). The kinetics of growth on these services is quite different, with smooth morphology obtained on the (0001) surface but rough morphology found on the (0 0 0 -1) surface, as shown in panels (c) and (d) (gray scale ranges there are 15 and 23 nm, respectively).

On the basis of recent theoretical results obtained by our collaborators (J. Neugebauer and J. Northrup) we can now understand this difference in growth kinetics from an atomic point of view, as shown on the second slide. Nitrogen atoms on the(0001) surface have zero energy barrier to move into a *subsurface* position between the In and In/Ga layers. In this subsurface position they have a significantly reduced diffusion barrier (about 0.5 eV compared to >1 eV for ontop diffusion on either of the (0001) or (0 0 0 -1) surfaces).

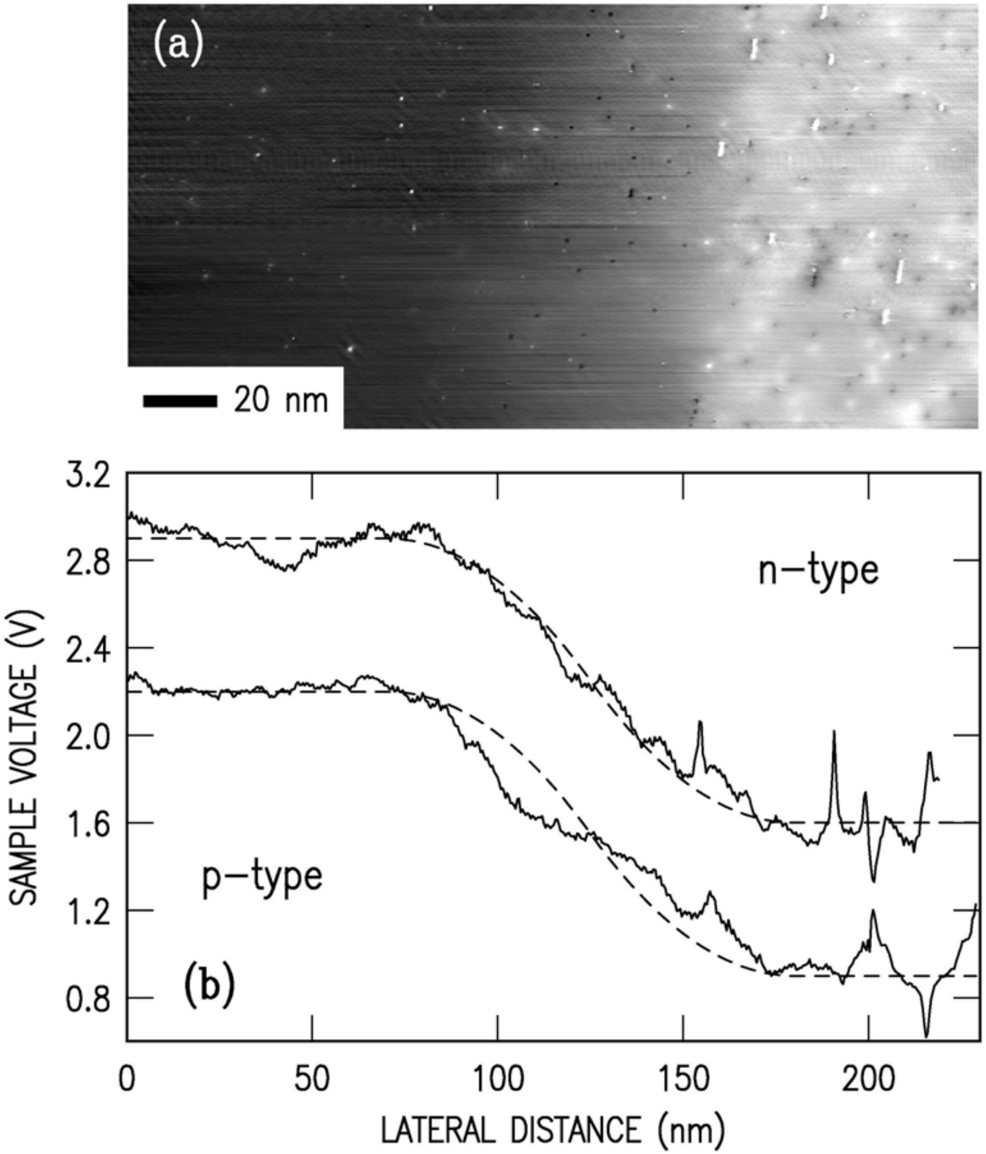
We therefore predict and observe smooth growth for InGaN growth on (0001) oriented surfaces, which is advantageous for device applications. (InGaN is the material used for blue light to emitting diodes and lasers).

Subsurface diffusion of N atoms (theory)



- indium adlayer distorts to accommodate diffusing N atoms
- surface diffusion barrier ≈ 0.5 eV << 1.3 eV without adlayer
- adlayer also reduces diffusion barrier for Ga atoms

Profiling of Electron Potential in Semiconductors



Scanning tunneling microscope image, showing regions of n-type and p-type doped layers.

Potentiometric scan, yielding directly the variation in electron potential through the device (two sample scans are shown, with different starting voltages).

Modern-day semiconductor devices function by tailoring the potential energy for electrons through the device, causing them to flow into a desired direction when an appropriate voltage is supplied to the device. We have developed a new measurement method for the scanning tunneling microscope which enables us to directly measure the variation in electron potential energy (electrostatic potential) through a device. Results are shown here for a semiconductor diode consisting of neighboring layers of n-type and p-type material. These differently doped regions can be seen in the constant-current image shown in panel (a). Similar images (which qualitatively reflect the variation in electrostatic potential) have been obtained in the past by many researchers. With our new method we can then scan the probe tip across the surface and directly measure the variation in electron energy, as shown in panel (b). Our results are in very good agreement with those expected on the basis of a simple model for this device as indicated by the dashed line.

This type of potential measurement has been attempted in the past by combining spatially resolved spectroscopic measurements with a detailed analysis, as accomplished in only one study by E. Yu and co-workers (E. T. Yu, M. B. Johnson, and J.-M. Halbout, Appl. Phys. Lett. **61**, 201 (1992)). With our new method the measurement is accomplished directly in a single scan, with no subsequent analysis. Our results will be published shortly in J. Vac. Sci. Technol B, Jul/Aug (2002).

Outreach
Prof. Feenstra has performed two outreach activities in the past year, both involving making a presentation on "Exploring the Nanoworld", based on the booklet and kit on the subject put together by Prof. Ellis and co-workers at U. Wisconsin-Madison. One of these activities took place in Berlin while Prof. Feenstra was on sabbatical there in the Fall of 2001, at the John F. Kennedy American High School to a group of 8th grade students in their Physics class. The second activity was at Carnegie Mellon University in Pittsburgh in March, 2002, to a group of the fifth grade students from a Pittsburgh inner-city school.

Honors
1. Prof. Feenstra received a Humboldt Research Award in 2001, which allowed him to take a sabbatical leave in Berlin for Fall 2001 during which time he undertook low-temperature scanning tunneling microscopy studies.
2. Prof. Feenstra was appointed Editor in Chief of the MRS Internet Journal for Nitride Semiconductor Research, starting in March, 2002.